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Studying of EDFA Performance for Different Concentrations of Erbium Atoms in the Energy Levels

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ABSTRACT
This paper presents a design of new Erbium Doped Fiber Amplifier (EDFA) configurations to get higher gain and lower noise figure (NF) values, at 1480nm wavelength, for 14mW pump signal and input signal -40dBm of wavelength 1550nm.
The paper includes modeling of EDFA utilizing Giles and Desurvire model for numerical analysis of rate equation model in MATLAB.
It also studies the effect of the pump power and pumping direction on the erbium population density per cubic meter along EDFA and then on the gain and noise figure values. All results and graphs are simulated using MATLAB software.
***Keywords* :—** EDFA Amplifier, ASE, Noise Figure, WDM

I. INTRODUCTION

Optical amplifiers are of great importance because they can achieve long-range communications via optical fiber. These amplifiers compensate the signal attenuation and renewing it.
EDFA is very popular for long distance communication applications, rather than electro-optic amplifiers that use optical- electrical- optical repeaters which are complex and expensive for multi-wavelength high capacity systems [1].
Therefore EDFA is widely used in wavelength division multiplexing systems [2].
In 1986, AT & T Bell Labs began research into optical amplifier, and in subsequent years many groups around the world contributed to the rapid development of EDFAs. In 1989, the newly developed InGaAsP laser valves were first used to pump EDFA with a 1480nm pump. In 1989, the first subsea test of erbium doped fiber amplifiers was done in a fiber optic transmission cable.
Clearly, such research has led to higher data rates, shorter transmission times and lower costs. As it is today's promising technology for medium- and long-distance communications, there is a need for a large-scale exploratory study of broadband optical amplifiers. The improvement of the capacity and cost of the new generation of optical communication systems depends on the development of EDFA amplifiers [3,4].
Using technologies and devices available in the WDM system, commercial systems transmit more than 100 channels on a single fiber, but, optical noise caused by Amplified Spontaneous Emission (ASE) limits the number of amplifiers. Therefore, the installed systems should be developed without adding new fibers, and new WDM systems can be built at a much lower cost. This shows the importance of gain and noise improvements in the EDFA design [1,2].

This paper focuses on the two-level EDFA amplifier designing by solving the system model equations in MATLAB based on the rate equation, (Giles and Desurvire model) [5]. The improvement of EDFA gain and noise is also studied. Besides, the physical properties of new EDFA configurations such as gain, noise factor, population density and amplified spontaneous emission noise are studied for different pumping directions.

The paper is organized as follows: section (2) describes the erbium doped fiber amplifier. The description of EDFA modeling is described in section (3). Section (4) gives implemented simulation results and discussion. Finally section (5) is a conclusion of the work.

II. ERBIUM DOPED FIBER AMPLIFIER

The EDFA amplifier essentially consists, as shown in Fig.1 of:

- Erbium doped fiber amplifier.
- Laser pump.
- selective wavelength coupler.

The optical wave and pump signal are injected into the EDFA by the WDM mux. The isolator is usually placed on the output of the amplifier to prevent reflection and return [5].

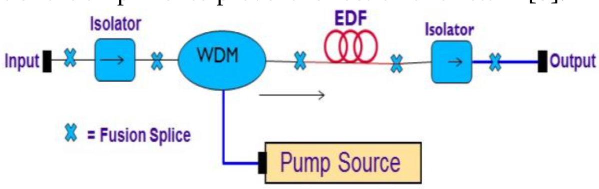

Fig. 1 Components of optical amplification system using EDFA

EDFA is the most commonly used amplifier since the amplification window is corresponding with the third optical transmission window, which, the optical fiber attenuation at 1550nm is minimal, so most commercial EDFAs operate in the C band (1530nm-1565nm), but the bandwidth is expanding to include L band (1565nm-1625nm) also in recent years.

The EDFA gain is obtained through the stimulated emission, There are several pump wavelengths suitable to pump the ions of the erbium to a higher energy level, now 980nm and 1480nm wavelengths are used and have proven to be the most effective wavelengths [6].

A. *Gain for EDFA:*

Gain is the main property of the amplifier. The EDFA gain is defined as the ratio of the output signal to the input signal as shown in equation (1) [1,7].

$$G(\lambda)=\frac{P_{out}}{P_{in}}=\int_0^L g(\lambda,z)dz=\int_0^L (g(\lambda)N_2(z)-\alpha(\lambda)N_1(z))dz \quad (1)$$

$$=4.3\Gamma_s(\lambda)[\bar{N}_2\,\sigma_S^e(\lambda)-\bar{N}_1\,\sigma_S^a(\lambda)]L$$

$g(\lambda)$ is gain coefficient; it is calculated by multiplying the sum of the emission factors and partial ions in excited state and absorption coefficient,the is Γ_s. $g(\lambda)=\Gamma_S N\sigma_e(\lambda)$ intersection of signal and ion. $\alpha(\lambda)=\Gamma_s N\sigma_a(\lambda)>0$,σ_s^e,σ_s^a is cross section of absorption and emission for signal wavelength.

N_1, N_2 is mean values of population densities of erbium ions in ground and excited states.

B. *Noise in EDFA:*

Most optical applications in communications, sensors, signal processing, etc. require detection and subsequent conversion of optical signals into an electrical signal. Thus, the useful signal will be damaged due to noise and limit system performance due to noise.

If the multistage EDFAs can compensate this signal loss, the question arises whether it is possible to pass a long distance randomly in fibers by periodic amplification along the fiber link, without limiting the dispersion effects of distance. In fact, this is not possible because noise is added by each amplifier.

As the ions of the erbium that occupy the highest level of energy can also make spontaneous transitions to the ground state and emission radiation just like the optical signal, and the spontaneous emission generated at any point along the fiber can be amplified, this is called ASE. It is possible to filter and remove any ASE that does not match the wavelength of the signal using a filter, but ASE cannot be filtered when it is placed inside the signal band. The minimum noise is added by the amplifier, as shown in Fig. 2 below [8].

Fig. 2 Amplified Signal Spectrum with ASE

ASE power is:

$$P_{ASE}=2\eta_{SP}(G-1)h\nu B_0 \quad (2)$$

ν: optical frequency, B0: optical bandwidth, h: Blank constant, G: amplifier gain, and spontaneous emission factor is:

$$\eta_{SP}=\frac{N_2}{N_2-N_1} \quad (3)$$

N2, N1 represent densities (the number of atoms per volume) in the upper and lower energy amplifier levels of the erbium in the fiber [9].

We should take into account the fact that N1 and N2 both change along the fiber because they depend on the pump and signal power. As a result, the noise depends on the length of the amplifier L and the pump power, just as in the case of the gain of the amplifier.

The ASE effect is determined by the NF given by:

NF = 2ηsp (4)

which in turn depends on both N1 and N2.

C. *Level System for EDFA:*

Mathematical expressions are used to develop a model to simulate the EDFA amplifier based on ordinary single-dimensional linear differential equations for the number of time-dependent ions in the EDFA. The general model of the erbium doped fiber amplifier can be considered a triple or two-level atomic system. There are three levels of pumping the erbium, the ground level with the density of N1 atoms, and the second level is excited state; it IS also called metastable N2, and the third level is excited level of N3 density. Fig. 3 shows the energy level for Er^{+3}[10,11].

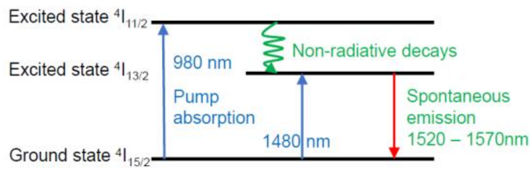

Fig. 3 Erbium ion transitions between energy levels

As shown in Fig. 3, the 980nm pump stimulates the electrons from the ground level to the third level, but soon returns quickly and accumulates in the second level to move to the ground level. When the number of electrons in the metastable state is greater than the ground state, the population inversion occurs, while for the pump 1480nm the electrons move to the metastable level and return quickly to the ground level.

Pumping at 980nm provides less noise than pumping at 1480nm. On the other hand, the 1480nm pump has a higher quantity efficiency, thus giving higher output power so it is preferred in the amplifiers.

The rate equation for the two levels is given as follows [12-14]:

$$\frac{dN_2}{dt}=-\Gamma_{21}N_2+(N_1\sigma_S^a-N_2\sigma_S^e)\phi_S-(N_2\sigma_p^e-N_1\sigma_p^a)\phi_p \quad (5)$$

$$\frac{dN_1}{dt}=\Gamma_{21}N_2+(N_2\sigma_S^e-N_1\sigma_S^a)\phi_S-(N_1\sigma_p^a-N_2\sigma_p^e)\phi_p \quad (6)$$

$\sigma_p^a, \sigma_s^a, \sigma_s^e$ and σ_p^a are the cross section of the absorption and emission of both the pump and the signal respectively.

ϕ_p and ϕ_s are pump and signal flow power. Γ_{12} is the probability of moving from level 2 to 1. In the case of Erbium Er^{+3}, $I_{13/2}^4$ represents level 2 and $I_{15/2}^4$ represents level 1.

$\Gamma_{21} = 1/\tau_2$, Where τ_2 is the life time in level 2.

Population inversion is achieved in the EDFAs amplifier as a result of the pumping of the fiber with the pump signal. The electrons at the ground energy levels rise to the excited level by the pump photons. The amplification takes place at the time of the population inversion between two levels 1 and 2, and at least half the total number of erbium ions in level 1 should be raised to level 2 to obtain the population inversion.

Total population density is given by

$$N = N1 + N2 \tag{7}$$

$$\frac{dN_1}{dt} = \frac{dN_2}{dt} \tag{8}$$

N2 can be calculated with a relationship associated with the intensity of the signal and the pump I_S, I_P and N1=N2-N.

III. NUMERICAL MODELING

In this section, an analytical evaluation of a silica-based EDF is presented for C-band operations. Since the EDFA uses pump wavelength of 1480nm, the two energy levels systems are considered.

For modeling an EDFA, we use the rate equations (4) and (5), that describe the amplifier's work, and depend on the Giles and Desurvire model, which according to it, the population densities are calculated as below [15-17]**:**

$$N_1 = \rho \frac{1 + W_{21}\tau}{1 + (W_{12} + W_{21})\tau + R\tau} \tag{9}$$

$$N_2 = \rho \frac{R\tau + W_{21}\tau}{1 + (W_{12} + W_{21})\tau + R\tau} \tag{10}$$

Where W_{12} and W_{21} are stimulated absorption rate and stimulated emission rate respectively, R is the pumping rate, τ is the fluorescence lifetime, and $\rho = N_1 + N_2$ is the total E_r^{+3} ions density per unit volume. The value of W_{12}, W_{21} and R, are given as below:

$$R = \frac{P_P^+ \Gamma_P \sigma_P^a}{h\nu_P A} \tag{11}$$

$$W_{12} = \frac{\sigma_S^a \Gamma_s}{h\nu_s A}(P_S^+ + P_{ASE}^+ + P_{ASE}^-) \tag{12}$$

$$W_{21} = \frac{\sigma_S^e \Gamma_s}{h\nu_s A}(P_S^+ + P_{ASE}^+ + P_{ASE}^-) \tag{13}$$

ν_S and ν_P are the signal and pump frequencies respectively. Γ_S and Γ_P are the overlap factors of the signal and the pump respectively. It represents the overlap of the erbium ions with the mode of the signal light field and pump light field, A is the effective cross sectional area of the distribution of erbium ions, h is the Planck constant, P_S^+ is the forward signal power, P_S^- is the backward signal power which is equal to the final signal output power of EDFA and P_P is the pump power of EDFA. P_{ASE}^+ and P_{ASE}^- are the forward and backward spontaneous emission powers of EDFA respectively. The values of all the above parameters for C-band are shown in Table 1 [18].

TABLE I
PARAMETERS FOR C-BAND EDFA [18]

L	15m	h	$6.626068 \times 10^{-34} j.s$
τ	0.102sec	ν_s	$193.45 \times 10^{12} Hz$
σ_s^a	$2.910556 \times 10^{-25} m^2$	ν_p	$202.40 \times 10^{12} Hz$
σ_s^e	$4.118853 \times 10^{-25} m^2$	A	$1.633 \times 10^{-11} m^2$
σ_p^a	$2.787671 \times 10^{-25} m^2$	$\Delta\nu$	3100GHz
σ_p^e	$0.810563 \times 10^{-25} m^2$	α_S	0.20dB/km
P_p^+, P_p^-	7mW, 7mW	α_P	0.24dB/km
P_S	-40dBm	Γ_S	0.74
ρ	300ppm	Γ_P	0.77

The forward signal power, backward signal power, pump power, forward ASE and backward ASE are represented by P_S^+, P_S^-, P_P, P_{ASE}^+ and P_{ASE}^-. The values of all the powers can be calculated by the following equations based on the Giles and Desurvire model [15-17]:

$$\frac{dP_P^+}{dz} = P_P^+ \Gamma_P (\sigma_P^e N_2 - \sigma_P^a N_1) - \alpha_P P_P^+ \tag{14}$$

$$\frac{dP_P^-}{dz} = P_P^- \Gamma_P (\sigma_P^e N_2 - \sigma_P^a N_1) + \alpha_P P_P^- \tag{15}$$

$$\frac{dP_S^+}{dz} = P_S^+ \Gamma_S (\sigma_S^e N_2 - \sigma_S^a N_1) - \alpha_S P_S^+ \tag{16}$$

$$\frac{dP_{ASE}^+}{dz} = P_{ASE}^+ \Gamma_s (\sigma_s^e N_2 - \sigma_s^a N_1) + \sigma_s^e N_2 P_P^+ \Gamma_s h\nu_s \Delta\nu - \alpha_s P_{ASE}^+ \tag{17}$$

$$\frac{dP_{ASE}^-}{dz} = -P_{ASE}^- \Gamma_s (\sigma_s^e N_2 - \sigma_s^a N_1) + \sigma_s^e N_2 P_P^+ \Gamma_s h\nu_s \Delta\nu + \alpha_s P_{ASE}^- \tag{18}$$

Where $\Delta\nu$ is the bandwidth of the ASE and z is the coordinate along the EDFA.

The first order differential equations (14) – (18): First we have used Runge-Kutta method to obtain a set of approximate solutions and then relaxation method is used to make iterative adjustment to the solution for more accuracy.

IV. RESULTS AND DISCUSSION

The main objective of this research is to propose EDFA configuration to overcome the high NF problem when pumping at 1480nm.

It is possible to use one or two pumps forward, backward or bidirectional for one stage or multi stages of amplification.

A very low pump power of 14 mW is considered at the input of the EDFA in this work. Now the length of the EDFA is needed to be optimized with respect to the input pump power to achieve maximum gain and low NF.

The effect on the number of erbium ions concentration in energy level 1 and 2 with the variation of fiber length has also been analyzed to determine the optimum fiber length.

Using a pumping power of P_P = 14mW and the signal capacity of P_S = -40dBm corresponds to $10^{-7}W$. The length of the fiber is 15m and the pumping wavelength is 1480nm. Several methods have been proposed to pump the EDFA amplifier with one or two pumps forward, backward or bidirectional. For each proposed configuration, the gain, NF and ASE noise were calculated.

A. EDFA Configuration1:

The EDFA amplifier is used in forward pumping. Fig.4 shows the schematic diagram for EDFA configuration1. The input signal was first sent to input 1 of circulator with one input and two outputs, the signal out of port 2, and input signal with 14mW insert directly to the EDFA amplifier of length 15m. The reflector is placed after the amplifier to reverse the resulting signal on the output of the amplifier and return it back to the amplifier with the pumping signal, so that the pumping signal is in the same direction as the amplified signal, ie, a second stage of amplification is achieved directly. After the second amplification step, the signal enters port 2 of the circulator to move to port 3, which represents the final output of this amplification process.

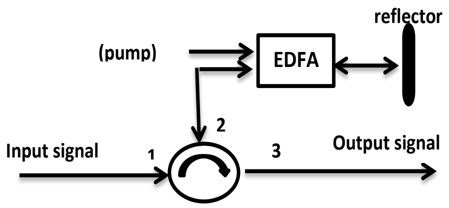

Fig. 4 EDFA configuration1

According to Giles and Desurvire, the population densities N1, N2, and the value of R can be calculated using Eqs. (9), (10) and (11), while to calculate W_{12} , W_{21} we must consider the reflected backward signal power P_S^- :

$$W_{12} = \frac{\sigma_S^a \Gamma_s}{h\nu_s A}(P_S^+ + P_{ASE}^+ + P_{ASE}^- + P_S^-) \qquad (19)$$

$$W_{21} = \frac{\sigma_S^e \Gamma_s}{h\nu_s A}(P_S^+ + P_{ASE}^+ + P_{ASE}^- + P_S^-) \qquad (20)$$

Fig 5. shows the upper state population and ground state population N1 and N2 respectively as a function of fiber length corresponding to 14mW pump power, -40 dBm signal power and $\lambda = 1550nm$. As N1 and N2 intersect at 21m, the optimum EDFA length for C-band operation is considered to be around 21m. As the EDFA length further increases, the gain will be saturated and the use of pump power will become inefficient.

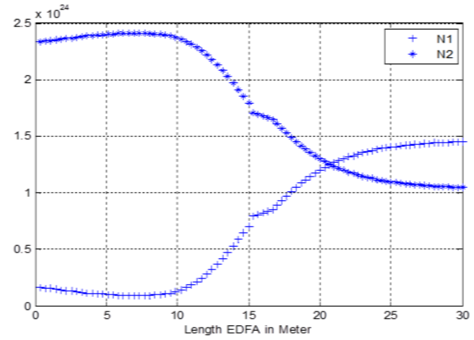

Fig. 5 Upper state population and ground state population as a function of fiber length for configuration1.

We noticed that the population in the second level is higher than the ground level, but after a certain distance, N2 begins to decrease along the fiber and at 21m it becomes less than N1. When N1 and N2 intersection occurs, the full pumping power is absorbed. This shows that at EDFA length of longer than 21m, the stimulated emission process starts to take power from the input signal power and thus degrades the gain and increases the noise figure. After this length, the induced emission process depletes the signal power, which results in a decrease in the realized gain and increases the NF.

Fig. 6 shows the signal gain as a function of EDFA length at 1550 nm using 14 mW of pump power.

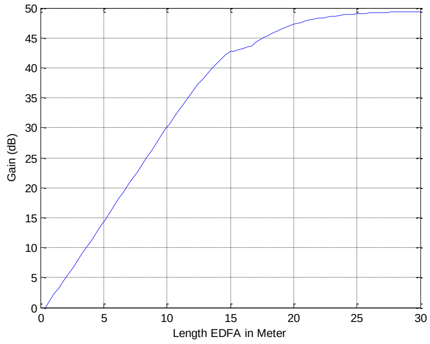

Fig. 6 Signal gain as a function of EDFA length for configuration 1.

From Fig. 6, it is seen that gain increases with the increase in length until the length of 21m, the gain stabilizes at 49.3dB. If an EDFA of length less than 21m is used then a portion of the pump power will remain unused which can cause more population inversion and hence the increment of the gain. For these reasons, an EDFA length of 21m is chosen as an optimized length for the proposed pumped EDFA configuration.

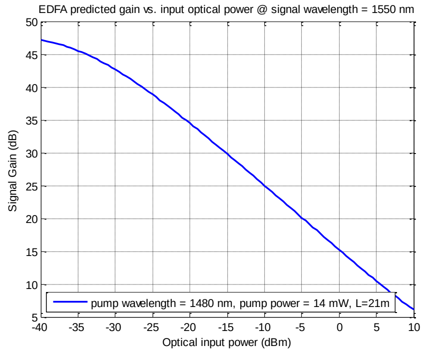

Fig. 7 signal gain as a function of signal power at L=21m.

Also we notice from fig. 7 that the signal gain decreases when input signal power increases at fiber length 21m, pump power 14mW, erbium ions concentration of 2.5e24 [$1/m^3$]. The gain saturation of EDFA is obviously seen from Figure 7. Under certain pump power, the signal gain keeps constant in a range of input signal power, and hence the output signal power increases linearly with the input signal power. However, the signal gain decreases when signal power further increases when all the pump power is consumed, and the output signal power trends to saturate accordingly. The gain saturation happens as the input signal power is increased, the more photons will enter the erbium-doped fiber stimulating emission of photons and depleting the metastable energy level faster than it can be filled. Therefore, the amplification will reach a limit and the gain will decrease with increasing input signal power.

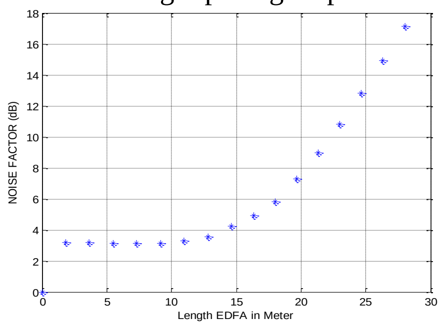

Fig. 8 Noise figure performance as a function of fiber length.

Fig. 8 shows the NF in dB as a function of EDFA length using a 14mW pump power at 1550 nm signal wavelength. From this figure, NF values are gradually decreased with the increment of EDFA length. This is because the population inversion increases with the increment of EDFA length.

B. EDFA Configuration2:

The setup of configuration2 is shown in Fig. 9. A 14mW backward pump signal with respect to the direction of the input signal has been used to design the EDFA.

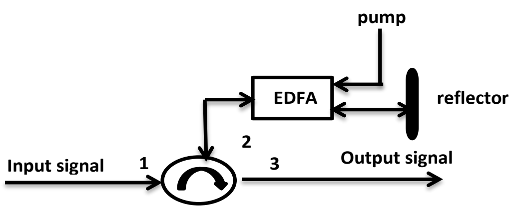

Fig. 9 EDFA configuration2

Depending on the Giles and Desurvire model in this case, consider the back propagation of the optical signal and the backward pumping. Thus $\frac{dP_s^-}{dz}, \frac{dP_s^+}{dz}, \frac{dP_P^-}{dz}, \frac{dP_{ASE}^+}{dz}, \frac{dP_{ASE}^-}{dz}$, NF, being calculated by using Eqs. (14)- (18), and W_{12}, W_{21}, R being calculated as in configuration1, Fig. 10 shows the erbium ions concentration versus fiber length curve.

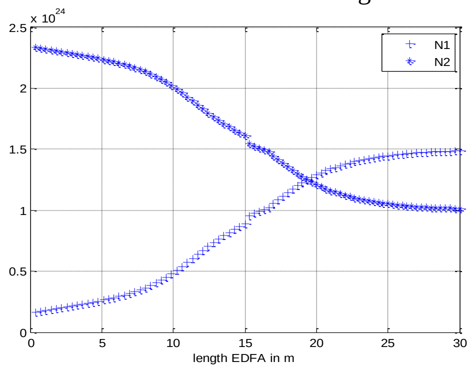

Fig. 10 Upper state population and ground state population as a function of fiber length for configuration2 .

From Fig. 10, after 19.33m length, upper state population is less than the ground state population. For this reason, if we use an EDFA of length more than 19.33m then the portion of the EDFA that exceeds 19.33m remains unpumped.

The use of an EDFA amplifier with a length of less than 19.33m increases the population inversion and therefore increases the gain.

For these reasons, 19.33m is the optimal length of the amplifier for this configuration.

Fig. 11 shows the signal gain as a function of EDFA length at 1550 nm using 14 mW of pump power for configuration 2.

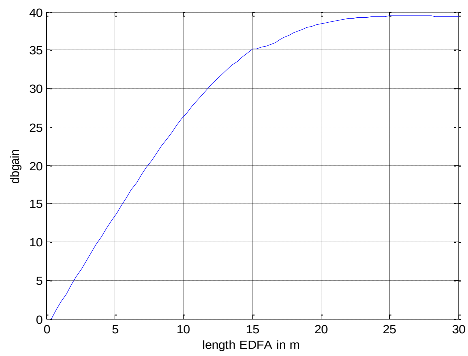

Fig. 11 Signal gain as a function of EDFA length for configuration 2.

In Fig. 11, The gain is maximum up to around 39.9 dB, and the NF is close to 9 dB around 19.33m, but it increases gradually up to 28 dB after 19.33m as seen in Fig. 12. Thus, the Configuration-1 has a better performance than Configuration-2 by both in higher output power and lower NF.

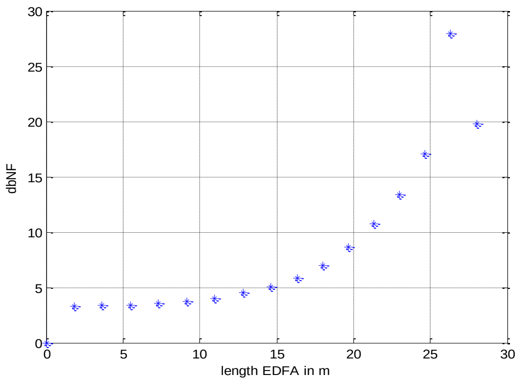

Fig. 12 Noise figure performance as a function of fiber length for 14mW pump power and -40dBm signal power.

C. EDFA Configuration3:

The setup for configuration3 is shown in Fig. 13. In this configuration, we divide the 14mW pump signal into two 7mW forward pump signals. The first forward pump signal with respect to the direction of the input signal is sent directly into EDFA together with the input signal obtained from the port 2 of the circulator. The second forward pump signal is sent into the EDFA in the same direction with respect to the direction of the mirror reflected signal.

The population densities N1, N2 , and the values of W_{12}, W_{21}, and R can be calculated as in Eqs. (9), (10), (19), (20) and (13), respectively.

The Giles and Desurvire model $\frac{dP_s^-}{dz}, \frac{dP_s^+}{dz}$, $\frac{dP_P^+}{dz}, \frac{dP_{ASE}^+}{dz}, \frac{dP_{ASE}^-}{dz}$, and Noise Figure NF will be calculated using equations (14)- (18), and (4).

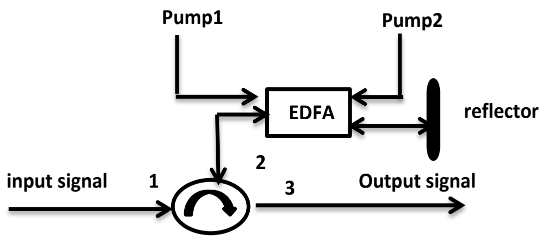

Fig. 13 EDFA configuration3

Fig. 14. shows the upper state population and ground state population N1 and N2 respectively as a function of fiber length.

Where 0-15m resembles the first pass and 15-30m resembles the second pass of the input signal through EDFA.

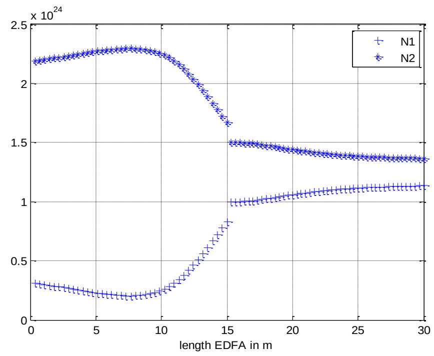

Fig. 14 Upper state population and ground state population as a function of fiber length for configuration3.

Fig. 15 shows the signal gain as a function of EDFA length at 1550 nm using 7mW of pump powers in the forward direction. The advantage of configuration3 compared to configuration1 is the increment of signal gain up to 30m, which value is about 39dB after 15m and reach about 50dB at 30m, while the Noise Figure is kept almost constant about 7dB after 15m.

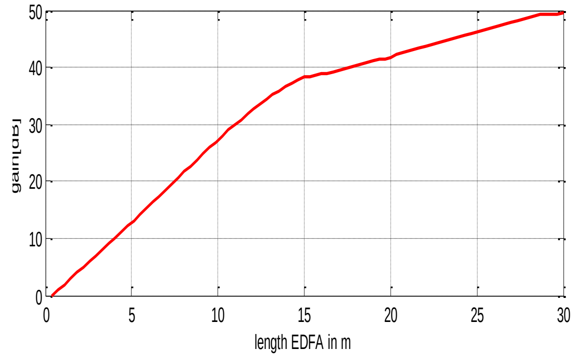

Fig. 15 Signal gain as a function of EDFA length for configuration 3.

Fig. 16 shows NF in dB as a function of 30 m long EDFA at 1550 nm signal wavelength.

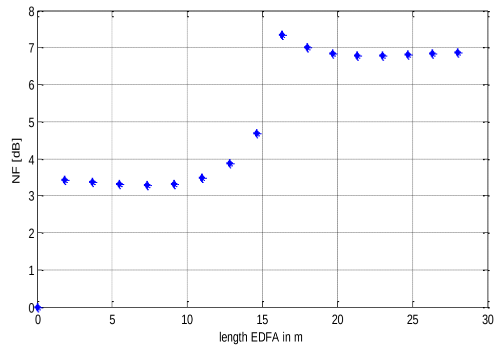

Fig. 16 Noise figure performance as a function of fiber length.

V. CONCLUSIONS

Three possible EDFA configurations have been presented in this paper. The performances have been compared with each other. This paper discussed the population density in ground and upper levels as a function of fiber length using different proposed configurations, and showed gain and NF for each configuration by utilizing Giles and Desurvire model. We proposed EDFA configurations different in the pump signal direction, where the two level system model equations are solved numerically in Matlab. EDFA configuration3 and configuration1 perform better than any one. For 14mW pump power and -40dBm signal power the gain for EDFA configuration1 and configuration3 is almost the same: it is about 50dB, but noise figure performance of configuration3 is the best and the value of it is within 7dB.

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